Engineering Failure Analysis 66 (2016) 72–87

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

The effect of residual stress due to interference fit on the fatigue behavior of a fastener hole with edge cracks

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ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form 5 April 2016
Accepted 11 April 2016
Available online 14 April 2016

Keywords:
Stress intensity factor (SIF)
Residual stress
Virtual crack closure technology (VCCT)
Fatigue crack growth rate (FCGR)
Riveting

ABSTRACT

The fatigue property of riveted lap joint is greatly related to the riveting-induced residual stress. However, an accurate study of the fatigue property considering the influence of residual stress quantitatively can be very difficult. A 3D interface element based on the virtual crack closure technology (VCCT) was developed to calculate the stress intensity factor (SIF) for through cracks at the hole edge. The riveting process was analyzed prior to the tensile test in the finite element code, so that the residual stress can be taken into account to get the eventual value of SIF. The result shows that, with the presence of fatigue cracks, the initial stress-strain state in the structure would change, especially near the crack tip, where great compressive stress can be found. The eventual residual stress cannot be derived by simply superimposing the riveting-induced residual stress with the crack-induced residual stress. The 3D-VCCT interface element shows strong ability to solve the SIFs. The FE analysis results agree well with the reported models both in the fatigue crack growth rate (FCGR) and in the shape of the crack front. However, when the crack is extremely short, not only the reported models, but also the present numerical model would fail. Besides, unlike Elber's model and Schijve's model, this study shows that the crack opening stress should not be a function of the stress ratio solely, but also with the crack length included.

1. Introduction

The rivet connection is widely used in the aeronautical industry, especially in pressurized fuselages of the aircraft. For the riveted fuselage, the structure integrity is significantly influenced by the residual stress in the hole vicinity induced by the riveting process [1]. The airplane can have a sudden failure of the joints of the load carrying skin and bring huge disasters, e.g. the Japan Air Lines Boeing 747 and the Aloha Boeing 737 accidents [2]. It was not due to the insufficient static strength of the plane, but fatigue failure caused these accidents. Under the cyclic fatigue load, the residual stress field in the sheet plays an important role in the nucleation and growth of cracks in the lap joints. As a result, it is necessary to study the localized stress/strain state at and around the rivet/hole interface and its influence on the fatigue property of the structure.

It has long been known that interference fit can improve the fatigue property of the riveted joints. The influence of the interference fit on fatigue is more like the influence of cold-working of rivet holes which would result in a compressive circumferential residual stress field around the hole. Experimental result shows that not only different fatigue lives but also different crack locations and fracture appearances could be resulted from different riveting loads [3–5]. It is generally taken that the improved fatigue behavior due to the interference fit, which could be enhanced by the increased riveting load, stems from an integrated effect of several mechanisms including the increased load transfer by friction, large area under rivet heads with compressive tangential

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http://dx.doi.org/10.1016/j.engfailanal.2016.04.012
1350-6307/

residual stresses near the hole, and less severe secondary bending in the outer rows in the rivet hole vicinity [3]. Although the factors that contribute to the fatigue behavior of a riveted structure are complicated, residual stress is usually considered of primary importance for a fatigue analysis. To account for the influence of residual stress on fatigue crack growth quantitatively, Liljedahl et al. suggest that two approaches can be used: the crack closure approach where the effective stress intensity factor (SIF) was computed and the residual stress approach where the effect of the residual stresses on the stress ratio was considered [6]. As the residual stress is frequently related to the plasticity-induced crack closure effect, the approach of the effective SIF is more widely employed [7–10]. To use such method, the influence of residual stress is either considered directly in a SIF in which a weight function is involved [10], or considered in a crack opening SIF in which the crack opening stress must be determined in advance by empirical formulas or experiment [11,12]. Unfortunately, in present models, the residual stress is often taken as a constant of the initiate state of the material, while the redistribution of the residual stress with the propagating cracks is overlooked [13].

Regarding the residual stress in a riveted lap joint, an accurate study may be much difficult because large deformation of plasticity could be involved, and the strain/stress in the plate, especially beneath the rivet head, cannot be measured directly by common methods. As a result, numerical simulation has long been the most frequently used method to learn the stress/strain in riveted metal sheets quantitatively [14–16], and the validity of these numerical models have been proved by experimental methods such as the X-Ray diffraction method, neutron diffraction method and the micro-strain gauges method [17–19]. To introduce the experimentally measured residual stresses in the finite element (FE) models, two approaches, using the SIGINI FORTRAN subroutine and using the eigenstrain, were also proposed by Liljedahl [6]. In Lacarac's work, the SIF was calculated directly via the finite element analysis (FEA), and the results were used to study the fatigue crack growth rate (FCGR) for cracks that emanated from cold expanded holes [20]. However, to use Lacarac's method for fatigue analysis, numerical calculation of the SIF must be implemented, which could be a very difficult problem for complicated structures resulted from several mechanical processes, e.g., a riveted structure, the manufacturing process of which comprises drilling and riveting before it is subjected to the final working load. Although many works reported the numerical method for SIF calculation [21–23], these methods cannot be used directly for the calculation of SIF in a riveted structure as they did not take into account the initial stress in the structure. Nevertheless, to analyze the fatigue property of riveted structures, the residual stress must be determined in advance and be included in the SIF calculation.

In the present work, the authors aim to study the influence of the residual stress on the fatigue property of the riveted lap joint. For a comprehensive understanding of the stress characteristics, the 3D finite element model of riveting process is employed as it is verified. For the analysis of crack propagation in the presence of residual stress, the strain energy release rate (SERR) and SIF were calculated on the basis of the virtual crack closure technology (VCCT) via the commercial FEA software ABAQUS with UEL (user defined element) subroutine [22,24].

2. Interface element based on 3D-VCCT

As the basic output variables in common commercial FE code, e.g., ABAQUS, do not cover the SERR or SIF, an interface element was defined in a subroutine which enables the calculation of the stated fracture parameters. The interface element is developed based on the original one-step-analysis called the modified crack closure integral (MCCI). Both 2D and 3D interface element based on the VCCT are comprehensively discussed in Prof. Xie's work [22,25], and a brief introduction is given hereby.

Suppose the crack lies in the x-y plane, the 3D interface element based on the VCCT can be defined by nine nodes, illustrated in Fig. 1, in which node 1 and node 2 are used to calculate the node forces at the crack tip, node 3 and node 4 are used to calculate the crack opening displacement behind the crack tip, and the rest nodes are used to calculate the area of the virtual crack propagation. As a result, only nodes 1 and 2 contribute to the element stiffness matrix. Other nodes, called “dummy nodes”, are only introduced to extract information for displacement and area calculations.

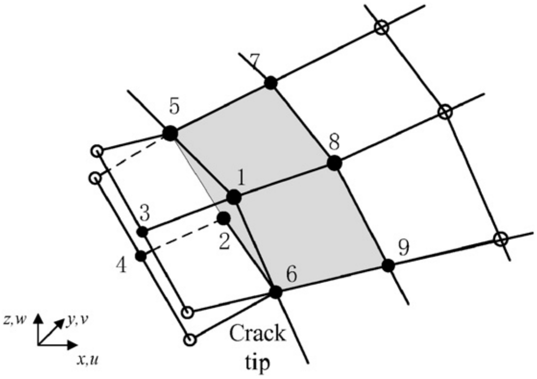

Fig. 1. Illustration of a 3D-VCCT interface element.